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Signatures of Coronal Heating Mechanisms

P. Antolin^{1,2}, K. Shibata¹, T. Kudoh³, D. Shiota⁴, and D. Brooks^{5,6}

¹ Kwasan Observatory, Kyoto University, Japan

² The Institute of Theoretical Astrophysics, University of Oslo, Norway

³ National Astronomical Observatory of Japan, Japan

⁴ The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan

⁵ Space Science Division, Naval Research Laboratory, USA

⁶ George Mason University, USA

Summary. Alfvén waves created by sub-photospheric motions or by magnetic reconnection in the low solar atmosphere seem good candidates for coronal heating. However, the corona is also likely to be heated more directly by magnetic reconnection, with dissipation taking place in current sheets. Distinguishing observationally between these two heating mechanisms is an extremely difficult task. We perform 1.5-dimensional MHD simulations of a coronal loop subject to each type of heating and derive observational quantities that may allow these to be differentiated. This work is presented in more detail in Antolin et al. (2008).

1 Introduction

The “coronal heating problem”, i.e., the heating of the solar corona up to a few hundred times the average temperature of the underlying photosphere, is one of the most perplexing and unresolved problems in astrophysics to date. Alfvén waves produced by the constant turbulent convective motions or by magnetic reconnection in the lower and upper solar atmosphere may transport enough energy to heat and maintain a corona (Uchida & Kaburaki 1974). A possible dissipation mechanism for Alfvén waves is mode conversion. This is known as the Alfvén wave heating model (Hollweg et al. 1982; Kudoh & Shibata 1999).

Another promising coronal heating mechanism is the nanoflare reconnection heating model, first suggested by Parker (1988), who considered coronal loops being subject to many magnetic reconnection events, releasing energy impulsively and sporadically in small quantities of the order of 10^{24} erg or less (“nanoflares”), uniformly along loops. It has been shown that both these candidate mechanisms can account for the observed impulsive and ubiquitous character of the heating events in the corona (Katsukawa & Tsuneta 2001; Moriyasu et al. 2004). How then can we distinguish observationally between both heating mechanisms when these operate in the corona?

We propose a way to discern observationally between Alfvén wave heating and nanoflare reconnection heating. The idea relies on the fact that the distribution of the shocks in loops differs substantially between the two models, due to the different characteristics of the wave modes they produce. As a consequence, X-ray intensity profiles differ substantially between an Alfvén-wave heated corona and a nanoflare-heated corona. The heating events obtained follow a power-law distribution in frequency, with indices which differ significantly from one heating model to the other. We thus analyze the link between the power-law index of the frequency distribution and the operating heating mechanism in the loop. We also predict different flow structures and different average plasma velocities along the loop, depending on the heating mechanism and its spatial distribution.

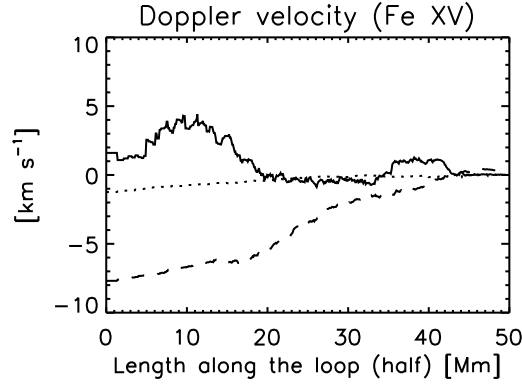


Fig. 1. Doppler velocities from synthesis of Fe XV 284.16 Å emission with respect to distance along the first half of the loop. The loop is assumed to be at disk center. The CHIANTI atomic database was used for calculation of the line profiles (Dere et al. 1997; Landi et al. 2006). The solid, dashed and dotted curves correspond respectively to Alfvén wave heating, footpoint nanoflare heating, and uniform nanoflare heating. Positive velocities correspond to redshifts (downflows).

2 Signatures for Alfvén wave heating

Alfvén waves generated at the photosphere, due to nonlinear effects, convert into longitudinal modes during propagation, with the major conversion happening in the chromosphere. An important fraction of the Alfvénic energy is also converted into slow and fast modes in the corona, where the plasma β parameter can get close to unity sporadically and spontaneously. The resulting longitudinal modes produce strong shocks which heat the plasma uniformly. The result is a uniform loop satisfying the RTV scaling law (Rosner et al.

Table 1. Observational signatures for coronal heating mechanisms. We consider Alfvén wave heating, nanoflare-reconnection heating with heating events concentrated at the footpoints (“footpoint nanoflare”) or uniformly distributed in the corona (“uniform nanoflare”). Second column: mean and maximum flow velocities. Third column: Doppler velocities derived from synthesized Fe XV 284.16 Å emission line. The loops is assumed to be observed from above (disk center). Fourth column: shape of the intensity flux time series. Fifth column: mean over the power law indexes obtained from intensity histograms for many positions along the loop from the footpoint to the apex.

Heating model	Mean & maximum velocities [km s ⁻¹]	Doppler velocities (Fe XV) [km s ⁻¹]	Intensity flux pattern	Mean power law index
Alfvén wave	$\langle v \rangle \sim 50$ $v_{\max} > 200$	red shifts ~ 3	bursty everywhere	$\langle \delta \rangle < -2$
Footpoint nanoflare	$\langle v \rangle \sim 15$ $v_{\max} > 200$	blue shifts ~ 7	bursty close to footpoints	$-1.5 > \langle \delta \rangle > -2$ decreases
Uniform nanoflare	$\langle v \rangle \sim 5$ $v_{\max} < 40$	blue shifts ~ 1	flat everywhere	$\langle \delta \rangle \sim -1$ decreases

1974; Moriyasu et al. 2004), which is however very dynamic (Table 1). Synthetic Fe XV emission lines show a predominance of red shifts (downflows) close to the footpoints (Fig. 1). Synthetic XRT intensity profiles show spiky patterns throughout the corona. Corresponding intensity histograms show a distribution of heating events which stays roughly constant along the corona, and which can be approximated by a power law with index steeper than -2 , an indication that most of the heating comes from small dissipative events (Hudson 1991).

3 Signatures for nanoflare reconnection heating

The nanoflare reconnection model consists of artificial injections of energy, simulating nanoflares which can be distributed towards the footpoints of the loop (“footpoint nanoflare heating”) or uniformly along the corona (“uniform nanoflare heating”). Strong slow shocks created by such heating events are only obtained in the first case, close to the footpoints. Fast dissipation of the slow shocks by thermal conduction leads to only weak shocks near the apex of the loop. We only obtain weak shocks in the case of uniform nanoflare heating. For both cases, the mean flow speeds are considerably smaller than in the Alfvén wave heating model (Table 1). Synthetic Fe XV emission lines show, mainly for footpoint heating, a predominance of blueshifts (upflows) close to the footpoints (cf. Fig. 1) which may match observations of active regions (Hara et al. 2008). In this case, spiky patterns result in XRT intensity profiles close to the footpoints, and a flattening of the profile at the apex. The corresponding power-law index of the heating events distribution decreases closer to the apex. In the case of uniform nanoflare heating, the intensity

profiles are not spiky but rather uniform in time due to the stronger dissipation by thermal conduction. It results in a very shallow average power-law index for the distribution of heating events.

4 Conclusion

The observable differences between the two coronal heating mechanisms are summarized in Table 1. The power-law index of the heating distribution is found to be sensible to the location of the heating along coronal loops and to the heating mechanism itself. Different flow patterns are also obtained. Downflows of hot plasma are present in the Alfvén-wave heating model, whereas hot upflows are obtained for nanoflare reconnection heating. Footpoint nanoflare heating seems to match the observations in active region loops better. Are Alfvén wave heating or uniform nanoflare heating more adequate for quiet-Sun loops?

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